Proceedings of the 7th JFPS International
Symposium on Fluid Power, TOYAMA 2008
September 15-18, 2008

P2-07

LOAD SENSING WITH ACTIVE REGENERATION SYSTEM

Pietro MARANI*, Gabriele ANSALONI* and Roberto PAOLUZZI*

* Institute for Agricultural and Earthmoving Machines (IMAMOTER-CNR)
National Research Council of Italy
Via Canal Bianco 28, 44100, Ferrara, Italy
(E-mail: p.marani@imamoter.cnr.it)

ABSTRACT

The paper introduces a novel system design of fluid power systems which improves the control and energy use for multiple actuators systems with particular focus on mobile applications such excavators, loaders, tractors. The system hereinafter described is based on a new patented technology [1], the "Load Sensing with Active Regeneration System". The main idea is to overcome one of the main drawbacks of multiple actuators conventional Load Sensing Systems: while the higher actuator load drives the pump delivery pressure the other active actuators are controlled by the local compensators in a dissipative mode. The goal of the novel architecture is to actively use pressure drops usually wasted in the local compensators and, in case of assistive or overrunning loads, dissipated over control valves.

KEY WORDS

Load Sensing , Active Regeneration, Energy Recovery, Control Valves

NOMENCLATURE

A_i : Cylinder Active Area at generic section i
F_i : External Force on Cylinder at generic section i
Q_d : Flow Rate at *Acceptor* Section **a**
Q_d : Flow Rate at *Donor* Section **d**
Q_i : Flow Rate at generic section i
Q_M : Flow Rate at *Dominant* Section **M**
Q_P : Flow Rate Supplied by the Pump
Q_R : Flow Rate Regenerated
T_i : External Torque on Motor at generic section i
V_i : Motor Displacement at generic section i
f_a : Load at *Acceptor* Section **a**
f_d : Load at *Donor* Section **d**
f_i : Load at generic Section i
f_M : Load at *Dominant* Section **M**
Δ : Effective Pressure Margin
ε_i : Linear Actuator Area Ratio at generic section i
ε_d : Linear Actuator Area Ratio at *Donor* section **d**

STATE OF ART

Nowadays the Load Sensing technology can be considered mature in many fields of application: Earth Moving Machinery (Excavators, Backhoe Loaders, Dozers…), Industrial and Road Construction machinery (Telehandlers, Compactors…), Agricultural and Forestry Machinery (Feller Bounchers, Tractors…).

Long time has passed since the appearance of Load Sensing Directional Valves, and in this period this technology has gained more and more importance on the market of mobile applications for two main reasons: the first is because of the control friendliness since the load movement is independent from the external load, and the second because of a better power management, in particular an outstanding energy saving is achieved in comparison with traditional open centre architectures.

A basic version of Conventional LS System is shown in figure 1. A single variable displacement pump supply the oil to a block of parallel directional valves. The pump "senses" the maximum actuators load (*Dominant Load*) through a chain of shuttle valves and sets the delivery pressure at a fixed level equal to the dominant load pressure plus a constant margin, the pressure drop that must be kept across the metering orifices (*Effective Pressure Margin*).

Copyright © 2008 by JFPS, ISBN 4-931070-07-X

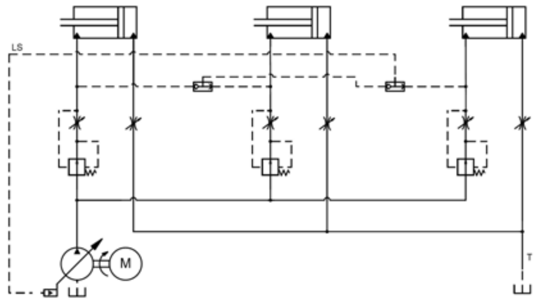

Figure 1 Conventional LS Architecture

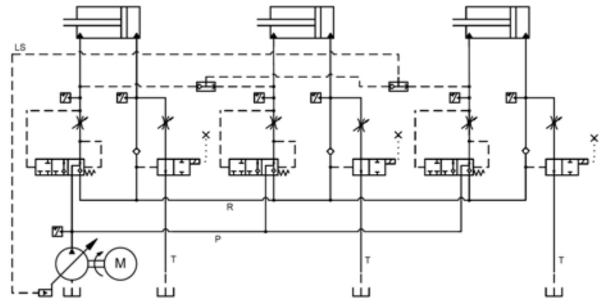

Figure 2 The ARLS Architecture

The pressure drop across the metering orifice at the *non-dominant* (*Dependant*) sections is controlled by throttling through the local compensators.

It is trivial to observe that, if the pressure difference between the loads is high a large amount of energy would be wasted through the local compensators (figure 3). At the same time it is evident that control strategy isn't favourable for assistive and overrunning loads as the system is intended for the meter in control.

A NOVEL ARCHITECTURE

One of the possible schemes of the architecture is shown in figure 2. Multiple hydraulic actuators are controlled by a valve block connected to a load sensing pump through the *P rail*. The LS signal is generated by means of cascade shuttle valves selecting the dominant load.

The valve *Discharge Flow Compensator* adjusts the pressure of the hydraulic actuator's outflow according to an electronic external command, rising the pressure on a secondary line called Regeneration rail or *R rail*.

The P rail and the R rail are connected to the inlet of *Upstream Compensator* adjusting the pressure drop across the metering to the effective pressure margin, the outlet of the valve feeds the hydraulic actuator.

The Upstream Compensator is a normally open three-position three-way valve. In the closed extreme position it disconnects the P and R rails from the Actuator; in the middle position connects the R rail but not the P, to the actuator regulating the flow from the R line; in the third position the connection of the R line is saturated open while the flow from the P line is regulated. Basically the actuator is fed so that R rail has priority on P line, in other words the actuator is fed by P line in case the R line has not enough flow rate or pressure to meet the required flow.

A unidirectional valve prevents the reverse flow from the actuator inlet to the R line; a second check valve prevents the reverse flow from the R line to the actuator outlet.

The control strategy is decided by means of the pressure transducers placed on inlets and outlets of hydraulic actuators that strategy consist on the decision of which Discharge Flow Compensator must be regulated or closed to rise the outlet pressure and direct the Outflow of the Actuator to the R rail. The pressure of oil flowing on the R rail must be enough to feed a second actuator. It must be noted that differently from other systems in which the outlet of some actuator is directly connected to a second actuator inlet, though without regulation, in the Active Regeneration Load Sensing System the flow delivered to each actuator is controlled in LS logic by the Upstream Compensator so that the flow always matches the request.

ENERGY CONSIDERATIONS

In Multi Actuator Hydraulic Systems two basic patterns can connect the supply to actuators and actuators to the tank: the first is a parallel architecture, the second is a series architecture.

The second architecture has the general drawback that the flow rate of actuators outlet must match the requested flow rate of the connected actuators inlet. It is trivial to note that if the flow rates always match Energy Management would be optimal: The pump delivers only the flow requested by the first actuator at the sum of loads pressures. Apart from hydraulic losses in pipes and valves, the energy requested exactly matches the energy delivered. It must be noted however that's very unlikely that the request of a actuator matches with the outflow of another in a machine work cycle.

On the other hand the parallel architecture can manage different flow requests by the actuators but, as discussed in many papers, has the drawback that the control of different loads connected to a single source is dissipative since the delivery pressure must be reduced to the level of the lower loads. It is easy to conclude that the if the loads are all equals the power management would be optimal because again apart from hydraulic losses in pipes and valves the energy requested matches exactly the energy delivered. In fact

Copyright © 2008 by JFPS, ISBN 4-931070-07-X

ideally the pump delivers the sum of flow requested by the actuators at the actuator's pressure (figure 3).

The Active Regeneration Load Sensing System combines the benefits of the two mentioned architectures, as it can work as a parallel Load Sensing System, but can also connect in series the actuators or realize a hybrid pattern in which a Actuator is fed both by the supply and by a Second Actuator Outflow. An important remark is that the control would always be optimal as the pressure drop across the metering orifices is fixed as in conventional LS systems (figure 4).

Some coarse Energetic Considerations can be drawn introducing some hypothesis and nomenclature.

i) The pressure drop on each metering orifice is fixed at the effective pressure margin Δ by the Upstream Compensator

ii) Maximum load (dominant load) section is labelled by letter **M**

iii) Donor section is labelled by letter **d** and its Actuator Outlet delivers flow to rail **R**

iv) Acceptor section is labelled by letter **a** and receives flow from rail **R**

v) The section **d** Discharge Flow Compensator is commanded to rise the Outflow from Actuator **d** pressure until the pressure on rail **R** reaches value $f_a+\Delta$ implying that the **R** line can supply fluid to Section **a**

vi) Flow rate at a generic section is Q_i, load at a generic section is f_i being F_i is the external force, T_i the external torque; A_i and V_i, respectively, Cylinder Active Area and Motor Displacement.

$$f_i = F_i / A_i \quad \text{or} \quad f_i = T_i / V_i \tag{1}$$

vii) Linear Actuator's Area Ratio is ε_i

viii) Oil flow rate in R rail is Q_R

The hypothesis lead to two possible cases:

CASE 1)

$$Q_a > \varepsilon_d Q_d \longrightarrow Q_R = \varepsilon_d Q_d \tag{2}$$

The oil flowing out from Actuator **d** is less than the Flow Request at section **a**: section **a** is fed at the same time by supply **P** and by regeneration rail **R**.

The flow Q_P supplied by the pump will be the sum of all requests minus the regenerated flow Q_R.

$$Q_P = \Sigma Q_i - Q_R = Q_M + Q_a + (1-\varepsilon_d)Q_d \tag{3}$$

In this case, see figure 5, the flow pattern is a hybrid beetween series and parallel configuration. The Discharge Flow Compensator at section **d** is completely closed.

CASE 2)

$$Q_a < \varepsilon_d Q_d \longrightarrow Q_R = Q_a \tag{4}$$

The flow out from actuator **d** is more than flow rate requested from section **a**: section **a** is completely fed from section **d**.

The flow Q_P supplied by the pump will be the sum of all requests minus the regenerated flow (equal to flow to section **a**).

$$Q_P = \Sigma Q_i - Q_R = Q_M + Q_d \tag{5}$$

In this case, see figure 6, the flow pattern of sections **d** and **a** is a series configuration. The Discharge Flow Compensator at section **d** is active, making some flow rate to be discharged to tank.

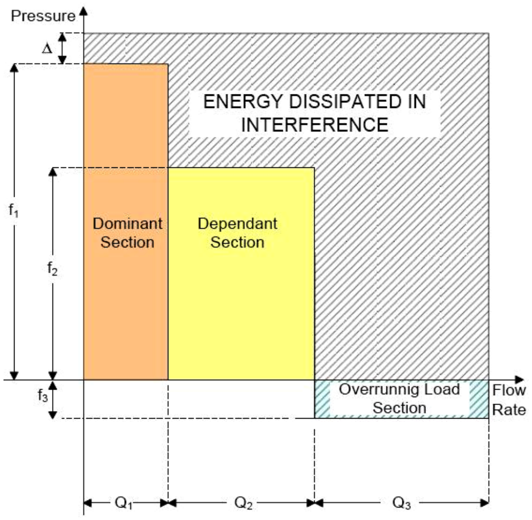

Figure 3 Conventional LS Architecture Energy Map

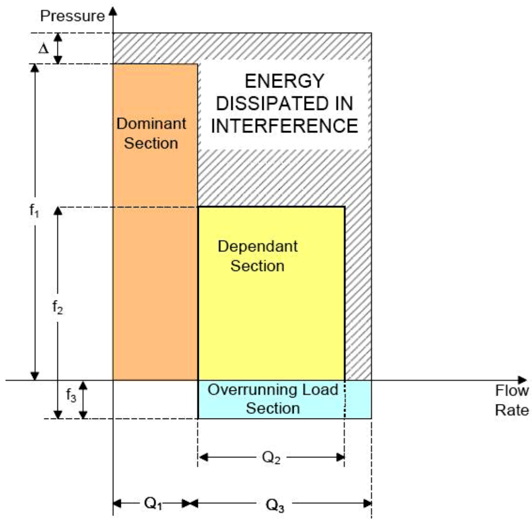

Figure 4 ARLS Architecture Energy Map

Copyright © 2008 by JFPS, ISBN 4-931070-07-X

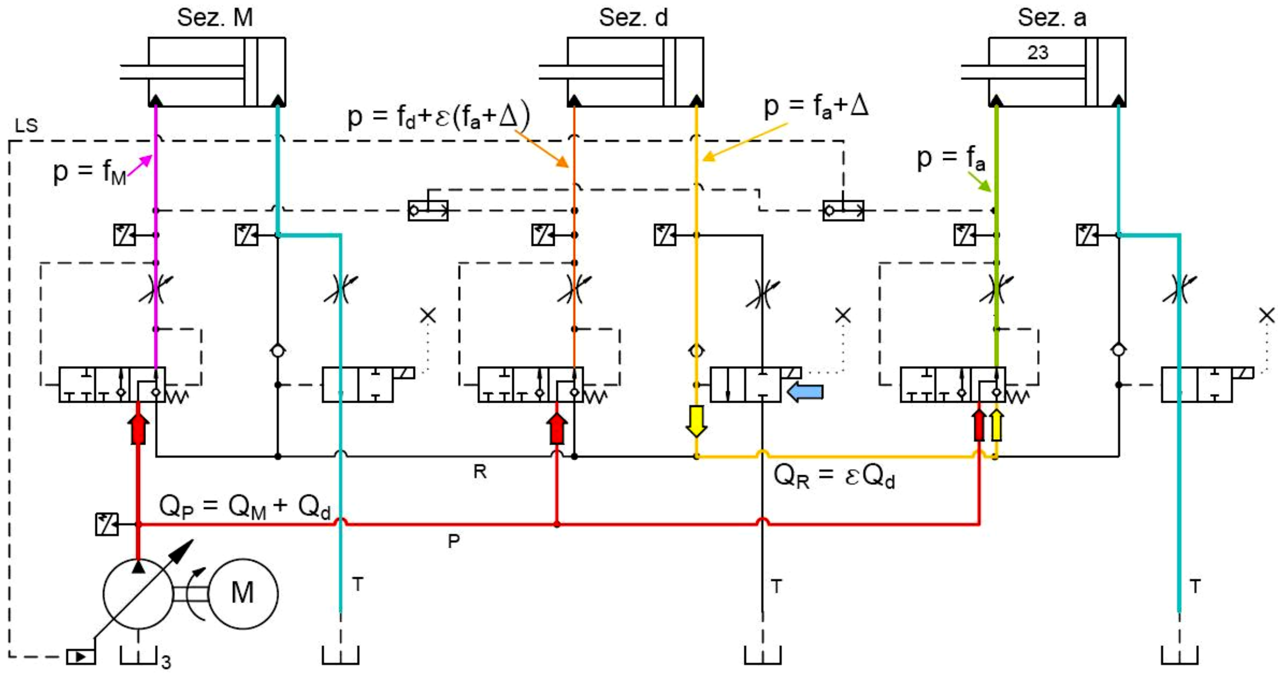

Figure 5 Active Regeneration Load Sensing System: Case 1 Flow Path

The touchstone for ARLS System is the conventional compensated LS system (figure 1). In this paper the approach is to make a comparison between the two; mainly as energy balance is concerned. Using equation (3), (5) it is possible to define the energy spent in a ARLS System (6). Similarly it is possible to write the Equation for the Energy spent in LS Systems (7).

$$W_{ARLS} = \left(\max\{f_d + \varepsilon(f_a + \Delta)); f_M\} + \Delta\right) \cdot$$
$$\cdot \max\{[Q_M + Q_a + (1-\varepsilon)Q_d]; (Q_d + Q_M)\} \quad (6)$$

$$W_{LS} = (f_M + \Delta)(Q_M + Q_d + Q_a) \quad (7)$$

$$W_{ARLS} < W_{LS} \quad (8)$$

Appling the equations (6), (7) to the Cases 1 and 2 it is possible to obtain two inequalities expressing the condition (8).

CASE 1) $Q_a > \varepsilon_d Q_d \longrightarrow Q_R = \varepsilon_d Q_d$

$$[f_M - (1-\varepsilon)f_d + (\varepsilon_d^{\,2} - \varepsilon_d)f_a + \varepsilon^2\Delta]Q_d >$$
$$> [f_d - f_M + \varepsilon_d(f_a + \Delta)](\Sigma Q_i - Q_d) \quad (9)$$

CASE 2) $Q_a < \varepsilon_d Q_d \longrightarrow Q_R = Q_a$

$$(f_M + \Delta)Q_a > [f_d - f_M + \varepsilon(f_a + \Delta)](\Sigma Q_i - Q_a) \quad (10)$$

In order to better understand the meaning of the energy balance above the concept is applied to three cases:

One featuring a single section regenerating on itself;

Two sections exchanging flow each other through regenerative rail R;

Three sections with two exchanging flow through the regenerative rail and the third working normally.

First Example Pattern: One Section Regenerating on Itself

Attention is focused on comparison between the two systems, obtaining two cases the first is that the Ratio Area is less than one, the second is that the Area Ratio is bigger than one. Suppose that a section is regenerating while other sections are working normally.

Case 1: Regeneration on section **d**, $\varepsilon_d<1$

$$(f_d - f_M)Q_d < [f_M - \frac{f_d + \varepsilon\Delta}{1-\varepsilon}](\Sigma Q_i - Q_d) \quad (11)$$

Observe that this inequality is always verified if the pressure induced by the Regenerated flow pattern is lower than the maximum load.

Case 2: Regeneration on section **d**, $\varepsilon>1$

$$f_d < -\varepsilon\Delta \quad (12)$$

This condition is verified only for high negative loads.

Copyright © 2008 by JFPS, ISBN 4-931070-07-X

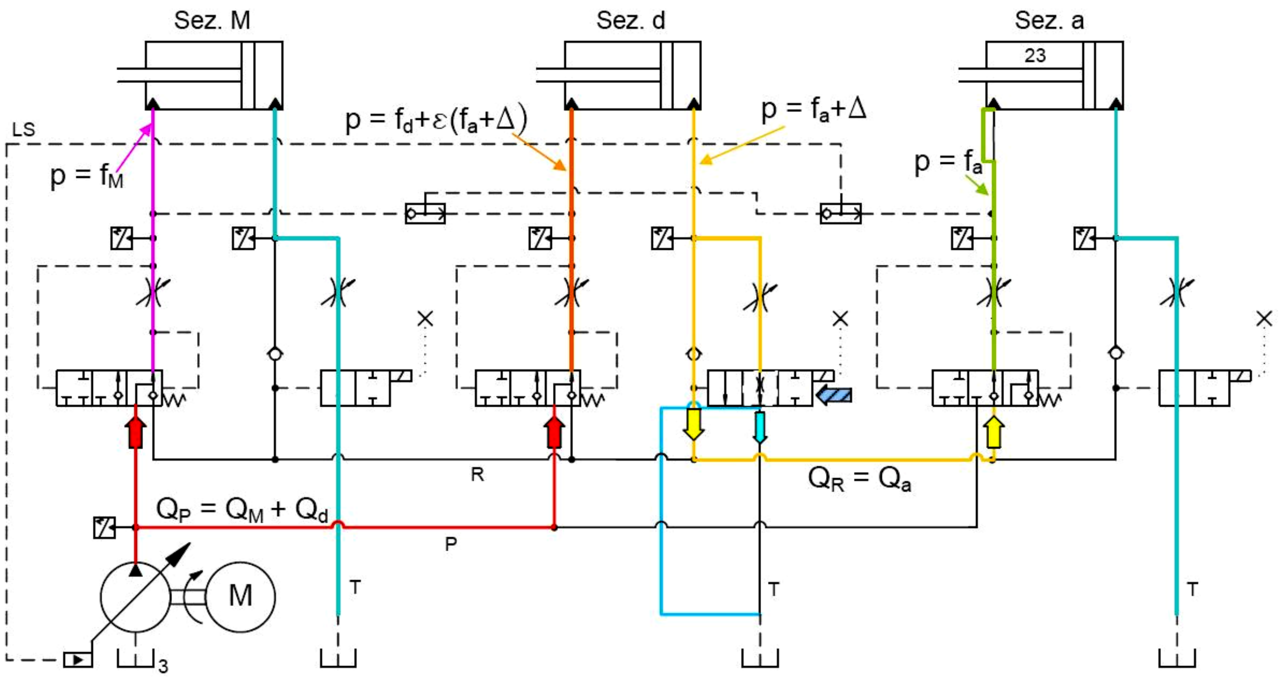

Figure 6 Active Regeneration Load Sensing System: Case 2 Flow Path

Second Example Pattern: Two Active Sections Regenerating

Applying the equations (9) and (10) to the case of two active sections with section **d** regenerating the flow to section **a** and supposing that the section at maximum load is the donor section **d** (assuming that the area ratio of actuator **d** is unitary) it is possible to obtain the following equations.

Case 1: $Q_a < Q_d$

$$(f_d + \Delta)Q_d > (f_a + \Delta)(Q_a) \quad (13)$$

$$\frac{f_d + \Delta}{f_a + \Delta} > \frac{Q_a}{Q_d} \quad (14)$$

Case 2: $Q_d < Q_a$

$$\frac{f_d + \Delta}{f_a + \Delta} < \frac{Q_a}{Q_d} \quad (15)$$

The two equations can be written simplified

$$\frac{f_d + \Delta}{f_a + \Delta} < \frac{Q_{max}}{Q_{min}} \quad (16)$$

where Q_{max} and Q_{min} are the higher flow rate and lower flow rate respectively.

Significant energy benefits of the ARLS architecture can be observed especially when the flow rates are close to each other and the loads significantly different.

Third Example Pattern: Three Active Sections, Two Regenerating

A fairly more complex, yet more significant example, includes three sections: one working normally, one donor and the third acceptor. We again consider unitary Area Ratio for sake of simplicity.

Case 1: $Q_a < Q_d$

$$[f_M + \Delta]Q_d > [f_d - f_M + (f_a + \Delta)](\Sigma Q_i - Q_d)$$

Some considerations can be drawn: if the dominant load exceeds the sum of other two loads plus effective pressure margin energy benefits are always obtained because the second term of equation becomes negative. It can be noted also that the greater the flow rate to the donor section the greater the energy saving is.

Case 2: $Q_d < Q_a$

$$(f_M + \Delta)Q_a > [f_d - f_M + (f_a + \Delta)](\Sigma Q_i - Q_a)$$

As in former Case it is favourable that the dominant

Copyright © 2008 by JFPS, ISBN 4-931070-07-X

load exceeds the sum of the other two loads plus the effective pressure margin. It can be noted at last that the greater the flow demand at acceptor section, the greater the energy saving is.

OTHER FEATURES

The Active Regeneration Load Sensing System has manifold assets. The feature discussed in the previous paragraphs is to have a flexible flow pattern to optimize the energy consumption, but many other possibilities arise.
The first is the possibility to use assistive or overrunning loads to aid the movement of other actuators without loosing Load Sensing control of actuators. It is widely recognized that a large amount of energy is nowadays wasted in operations such as lowering loads; the ARLS architecture makes possible the recovery of potential energy redirecting the Outflow from Overrunning Load Sections to other active sections.
The second is to have a regenerative function in Load sensing control. In traditional systems the regenerative function is an on off function unfitting the load sensing logic based on proportional control. In the ARLS system it is possible to activate a regenerative function as discussed in the first example pattern throttling the Discharge Flow Compensator while the pressure drop across the metering orifice is kept constant by the Upstream Compensator.
The third is to improve the control of assistive and overrunning loads: the load sensing system are designed for meter-in control, a positive load on the Outlet of the Actuator is better controlled in meter-out control. The Assistive load can cause in LS systems losing of load sensing control (i.e. control proportional to meter-in command) or Cavitation as the load sensing throttles the actuator inlet line to maintain the effective pressure margin on meter-in orifice. In the ARLS architecture the Discharge Flow Compensators can be used to control the Actuator's Outlet Pressure assuring an optimal controllability and preventing the Cavitation phenomena.
Another improvement with respect to traditional systems is that the meter-in function can be disjointed to the meter-out. In fact the distributor spool can be designed so that the supply to actuator connections has proportional feature and the actuator to tank has just directional feature and made all meter out regulations to be performed by the Discharged Flow Compensator.
An important feature is to move the saturation point of the system as the flow request is lower than or (as a worst case) equal to that occurring in traditional systems. In fact every time a regenerative path is activated the flow supplied by the pump reduces by the regenerated flow. Considering a stochastic distribution of flow requests configurations it is trivial that the use of regenerative paths can dodge the Flow Saturation Event.
One of the possible drawbacks of the system is that instability could arise since the hydraulic variables vary during the working cycles and consequently the control parameters and outputs change in time. Possible effects of discontinuities at the endstops of cylinders, flow and pressure saturations are also points which will need further attention. Fortunately first simulations show quite encouraging results on this side.

CONCLUSIONS

A novel Architecture the Active Regeneration Load Sensing System was presented demonstrating that it improves the control and energy use for multiple actuator systems. An energy comparison with respect to traditional LS systems was carried out stressing the energy benefits of the ARLS Architecture.
Additional work is needed to develop a prototype and to work out the control strategy to be embedded in an electronic controller and will be subject of further research in the field.

REFERENCES

1. Marani, Paoluzzi, Patent IT TO2007A000516, July 2007
2. Rivolier, Patent US 5,305,789 , 26/04/94
3. Satoru et ali, Patent JP 7,324,355 , 12/12/95
4. P. Marani, G. Ansaloni, R. Paoluzzi, A. Fornaciari, “Test Methods for Flow Sharing Directional Valves”. PTMC Symposium 2006, Bath, UK 2006
5. T. Virvalo, J. Seppälä, “Cross Utilizing degree Of Freedoms of Boom in Energy Saving Concept”. PTMC Symposium 2006, Bath, UK 2006
6. R. Rahmfeld, M. Ivantisinova, “Energy Saving Hydraulic Displacement Controlled Linear Actuators in Industry Applications and Mobile Machine Systems”. The Fourth International Symposium on Linear Drives for Industry Applications (LDIA03), Birmingham, UK 2003
7. G.L. Zarotti, N. Nervegna, “Saturation Problems in Load-sensing architectures”. Proc. of the 43rd National Conference on Fluid Power , IIT Center, Chicago, USA 1988

Copyright © 2008 by JFPS, ISBN 4-931070-07-X